

State of the Art of LED Technologies

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Taking C.I.E. in the name of this symposium serious, this review will relate primarily to ILLUMINATION, more precisely to Solid State Illumination. After a long time of dreams of scientists and engineers about *cold light*, *solid state lighting*, which did not materialize so far, the recent developments of Light emitting Diodes (LED) give much more hope for a timely realization. The reasons for the hope will be outlined, but at the same time caveats and problem areas will be addressed.

The most noticeable progress over the last years has been in signaling applications as traffic lights and automobile lights. The significant increase in efficiency of the red and amber LEDs has brought about a huge advantage over color filtered incandescent, which is close to an order of magnitude. Power LED lamps greatly simplified the construction, reducing the number of LEDs by a factor of 10 to 20 over previous designs. Also in displays, especially the very big ones, LEDs made a significant inroad, mainly because of steeply increasing availability of green and blue, (Ga,In)N-based LEDs.

A critical review will be presented of the recently reported best efficiency values, which surpass unfiltered incandescent, and approach halogen and compact fluorescent lamps. The efficiency — as well power efficiency, telling much more about the distance from margins, as luminous efficiency — depends strongly on drive conditions. A fact often neglected, but of ultimate importance in almost every practical application. Admitting that at least at present the chip itself is the dominant cost item, the lumen/chip-area or lumen-per-lamp is another important criterion. In this context a recently proven concept of power LEDs will be introduced.

In contrast to signaling, illumination requires additional properties, most noticeably reasonable color rendering. Except for niche applications, as night bar or karaoke or certain kinds of advertisement, white of certain color temperatures or CCT is wanted. Examples will be mentioned in which hundreds or thousands of LED have been combined and color mixed by secondary optics to demonstrate feasibility of solid state lighting. In general those demos to our opinion were excellent indicators of the long stretch to go to general lighting by LEDs.

Two major approaches to *White Light from LEDs* are feasible — a) mixing of primary colors from color-different chips either in one lamp package or by secondary optics, and b) color conversion by phosphors of blue or UV light from one chip and mixing within one package. While there is no multi-chip package on the market known to the authors, many *phosphor-converted LEDs* (pcLED) are marketed by various manufacturers. So far the preferred version is the one phosphor one. Here the blue light of the chip is partially converted into broad yellow, and mixed to white. Exploiting the phosphor used for some decades as color correction phosphor in high pressure discharge lamps - YAG:Ce³⁺ - rather good color rendering in the high CCT range can be achieved. Aiming at traditional indoor CCT values preferred in Europe and USA of around 3000°K the problem becomes more involved. Reasonable compromises between CCT and color rendering, expressed as the general rendering index, Ra, will be demonstrated.

A *de-luxe white* approach relies on two phosphors excited by the same blue LED, emitting green and red respectively. The mixing allows for Ra>90 at any CCT above 2500°K. Results on experimental lamps will be presented; an example is given in the figure.

Things get more complicated, if the need for selling as many lumen/\$ is taken into consideration, which means running the lamps at high power input, which in turn gives rise to temperature increase. Even with a proven package heat sinking as good as 12°C/W the temperature becomes an issue as outer heat sink temperatures might run off. Here an advantage of incandescent,

radiation cooling, comes to mind. Especially in general lighting and automotive applications the junction temperature may reach well above 100°C. Even in display back lighting this limit will be a lower one.

Hardly any of even the well-known phosphors temperature dependencies above room temperature of efficiency and spectral/color properties have been investigated, as for scientific reasons the behavior at low temperatures is more interesting and indicative of relevant mechanisms. However, if temperature independent color converters can be used in pcLED the lead over multi-chip LEDs is appreciable. In the latter case the temperature coefficients of phosphides (red/orange) and nitride (green/blue) based chips differ almost by an order of magnitude, and active output control is an absolute necessity.

While many niche applications can be traced in which costs are not essential, in a more general sense the lumen/\$ is a vital specification. While there is no doubt about the dominance of incandescent lamps in this category, other specs begin to catch customer appreciation — lumen*hours/\$ or cost of ownership including the energy consumption; the differences to incandescent shrink for both of them.

In conclusion one has good reasons to state, that LED are just ready to go for lighting and might in future raise the interest of CIE commission directly dealing with illumination.

